Chapter 5:
Observational Record of the Leonid Meteor Shower[3]

5.1 Introduction

Meteor Science in its modern form was born on the morning of November 13, 1833. It was the great Leonid return of that year which provoked widespread interest in the subject after being observed extensively in North America (Olmsted, 1834). With its unique nature of producing strong showers every 33 years, the Leonid shower is probably the most extensively written-about meteoroid stream. This observational database permits useful constraints to be placed on modern theories of the stream's evolution.

Numerous past works have examined Leonid records both ancient (e.g. Hasegawa 1993) and more modern (e.g. Mason 1995). However, in virtually all of these secondary works, no examination of the original records was attempted and the actual activity profiles, locations of peak activity and other characteristics are ill-defined. Our motivation is to re-examine as many original accounts of the shower contains usable numerical information as possible and determine the characteristics of past showers, independent of the many secondary accounts which appear in the literature, in an effort to better understand the stream's past activity and interpret its basic physical properties. These data will also provide the basis for comparison with the numerical modelling of the stream, which is developed in Chapter 6.

We examine the available original records of the Leonids for modern returns of the shower (here defined to be post-1832). In doing so, we attempt to establish characteristics of the stream near its peak activity, as borne out by the original records, for the years near the passage of 55P/Tempel-Tuttle. We utilize firsthand and original records of the shower for

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each year to construct activity curves for the shower. Using these data we then estimate the solar longitudes for each return for which significant activity occurred and the approximate time of peak activity.

5.2 Observations of the Leonids

In what follows we present a detailed, though by no means complete, examination of the original accounts associated with the Leonids between 1832 - 1997. The original sources consulted to form the activity profile for each year are given in the figure captions. A brief discussion of shower activity in the years where it is highest is given and mention made of previous errors found in secondary sources. Years not discussed are specifically omitted due to lack of access to the original observational material.

Leonid activity reported in the historical literature is based on visual observations of the shower. From the hundreds of original accounts examined, it became obvious that any attempt to produce a precisely corrected activity curve of similar quality to those derived from modern amateur meteor observations would be entirely impossible and quite misleading. In an effort to quantify what hard data does exist in historical accounts, we performed only three main corrections to the raw reported numbers: a correction for the elevation of the radiant, a correction for the total effective observing time; and (where needed) a correction for the number of observers reporting as a group. The aim of such a minimalist approach to the corrections is to provide a lower limit to the estimate of the zenithal hourly rate (ZHR) of the shower, as well as reducing the propensity for subjective interpretation of the historical shower record. In those rare cases where it is explicitly stated, the fraction of the sky covered by clouds during observations is also included (see Chapter 3 for a detailed account of the methods of reduction for the ZHR).

Recall that the ZHR is the number of meteors from the shower that an average observer would see in one hour of net observing under unobstructed skies with the radiant overhead and the faintest visible naked eye star in the field of view equal to +6.5 (see Eqn. 3.1).

The ZHR is not a direct measure of the flux from a shower. However, in those cases where the population index changes very little over the activity period of a shower, the variations in the ZHR are a good measure of the relative changes in the flux to the effective limit of visual meteor observations (magnitude ~+3 - +4).

None of the historical accounts provides quantitative estimates of the darkness of the sky (LM or limiting magnitude) and very few provide any distinction between sporadic and shower meteors. We are interested in determining the time of peak activity, an estimate of the ZHR at the peak and some indication of intervals where no obvious observations have been made (hence a storm might have gone unnoticed). As well, less precise information, such as the duration of the shower noticeably above the sporadic background and (for storms) the width of the storm producing segment of the stream is useful.

To this end we completely ignore the correction for sky brightness, noting that this is a sensitive function of *r* and that modern observations almost always produce sky brightness corrections greater than one, i.e. the LM is rarely better than 6.5 for most observations. Making this approximation will generally result in an estimate of the ZHR, which is a lower limit to the true ZHR. In particular, in conditions where large numbers of shower meteors are present, we expect that our estimate for the activity will be a true lower limit, in part due to the omission of the sky brightness correction term and in part due to saturation effects (cf. Koschack et al. 1993). The presence of the moon will also further decrease the visibility of the shower. This is noted qualitatively in the description for each activity profile and developed more in the discussion section.

In addition to ignoring the sky brightness correction, we assume no significant perception corrections. From modern observations, observer perceptions may vary by as much as a factor of ~3 but typically the deviations are much smaller (cf. Koschack et al., 1993; Jenniskens, 1994). Given that we have no precise means to incorporate these effects in the archival data, we leave out perception corrections.

As many older observations are reported as group observations, the correction factors reported by Millman and McKinley (1963) for reducing group observations to that of a single observer are utilized.

By using either minimal or no assumptions in the corrections for historical observations (pre-1988) we are attempting to provide a picture of Leonid activity that is as unbiased as possible. Note that for more recent observations (1988 - present) detailed estimations of sky brightness by observers are available and these data are incorporated to produce a more accurate ZHR profile.

To help further in interpretation we divide the historical observations into three quality categories: poor, medium and high quality. High quality observations are single observer reports with no cloud and with the radiant higher than 25° at the mid-point of the observation. For conditions where clouds are present but obscure less than 20% of the field of view, or radiant elevations are between 25° and 20°, or for group observations the records are considered medium quality. If two of the foregoing conditions are met for one observation, or for observations with the radiant below 20°, or for group observations which sum all meteors (i.e. multiple count single meteor events) the quality is automatically given as poor. Observations made with extremely small sections of the sky visible (i.e. through windows) or with radiant elevations below 15° are generally rejected outright.

The result of this process is activity curves (during years with little or modest Leonid activity) that are necessarily noisy but still contain enough information for us to conclude what lower limits may be reasonably placed on reported activity from past Leonid returns. Peak ZHRs, their locations (in terms of solar longitude - J2000.0 is used throughout) and other pertinent final information are given in Table 5.1 at the end. Note that we present here only an abbreviated form of the full discussion of each year's activity and concentrate instead on the final results and the most important Leonid returns (relative to the discussions in Chapter 6). A complete account can be found in Brown (1999).

5.3 Modern

The observing circumstances, comet-Earth geometry and details of the returns during each epoch from 1831-1997 are given in Table 5.1 (Section 5.5). For the strongest Leonid returns and those where enough observations of sufficient quality are available we have attempted to construct an activity profile for the stream based on these observations; elsewhere estimates of the peak time and associated rate only are given with appropriate references to the original material. All of this is summarized in Table 5.1.

5.3.1 The 1833 Epoch

The 1833 return has been described in detail by Olmsted (1834) and Twining (1834) where reports from throughout the Eastern and Southern US were collected together with reports from ships at sea. It is clear from the numerous accounts provided by Olmsted that the 1833 shower was quite broad, lasting for at least four and perhaps six hours. The time of maximum is stated by several independent observers to have occurred at approximately 13.4 Nov 1833. This time corresponds to more than an hour before astronomical twilight began over most observing locales in the Eastern US and fully two hours before the onset of civil twilight. Considering that at this time the radiant was still climbing in altitude, it seems likely that this represents the true time of maximum. The only precise numerical value for the 1833 display given by Olmsted (1834) refers to one observer from Boston who observed near 13.45 UT Nov 1833 and recorded 650 meteors in 15 minutes in heavy twilight. The observer further reports that his field of view was confined to less than 10% of the full horizon and that he missed at least 1/3 of the meteors. This yields an interpretation of the ZHR as >38 000 centred about this interval; the maximum rate slightly earlier must have been several times this number under darker skies. Olmsted also notes that this value probably underrepresented the true maximum strength of the storm. Henry (1833) observed the shower from Princeton, New Jersey close to sunrise and noted that, “When first seen by me they were so numerous that 20 might be counted almost at the same instant descending towards the horizon in vertical circles of every azimuth or point of the compass. While the exact meaning of “an instant” is not clear, it seems probable that this term reflects a meteor rate close to 20 per second. He also notes that a student outside at 9.5 UT (13.4 UT) recorded 1500 meteors "...in the space of a few minutes...". Taken at face value, and assuming a minimum of two minutes for the observation, we have a maximum rate of ~750/minute or ~13 per second in general accord with Henry's own observation. These observations (probably the best numerically available for the peak of the 1833 display) imply peak ZHRs in the range of 50 000 - 70 000, a finding also consistent with interpretation of the observation of 38 000 reported by Olmsted (1834) from Boston almost an hour later, as a lower limit to the peak activity.

The first vestiges of the shower were recorded reliably near 13.3 Nov 1833, while the display continued into daylight over the Eastern US until at least 13.5 Nov 1833. The best estimate of maximum is 13.4 UT Nov 1833 with a peak rate of 60 000. Other sources quote 50 - 150 000 /hour for the peak (Kazimirchak-Polonaskaya et al., 1968; Yeomans, 1981; Kresak 1980) but the basis for these values is not discussed in these works.

In addition to the major storm of 1833, the preceding year also showed unusual Leonid activity. The storm produced in 1832 lasted many hours on the night of November 12/13, 1832 from at least Nov 12.8-Nov 13.3 and was chronicled in South America (Olmsted, 1837), the Middle East (Rada and Stephenson, 1992; Hasegawa, 1997), Western Europe (Olmsted, 1834) and Eastern Europe/Russia as far as 60°E (Sviatsky, 1930; Quetelet, 1839) as well as North America (Arago, 1857). This return is variously mentioned as rich in fireballs and may have been quite intense, taking into account the moon's position near the radiant on November 13, 1832. No Asian records of this storm were made. Several of the accounts mention that unusual numbers of meteors were visible the night before (12 Nov 1832), suggesting a very broad activity maximum of bright meteors. Gautier (1832) reports average hourly rates near 2000 from Switzerland at approximately 13.2 UT November, 1832, the only numerical data available for the 1832 storm.

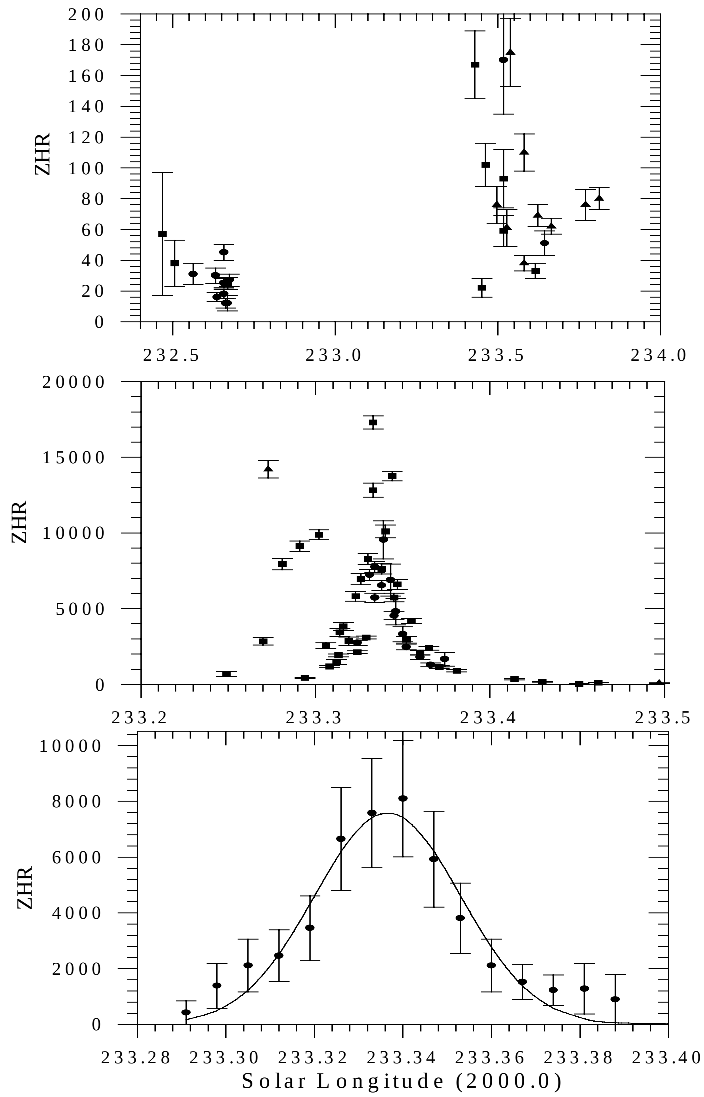


Fig 5.1: ZHR profile for the 1866 Leonid return. Data are taken from accounts given in Malta (Galea, 1994), Smyth (1867), Grant (1867), Main (1867), Newton (1867), De La Rue (1867), Dawes (1867), Hind (1867), and Cooke (1867). The top graph (a) shows the level of broader activity for a day on either side of the storm maximum (b) and (c) is a Gaussian fit (solid line) to the smoothed data in (b) using a smoothing window of 0.02° width shifted by 0.007° (10 minutes) in accordance with the shortest time counts.

5.3.2 The 1866 Epoch

The 1866 epoch was characterized by three strong Leonid returns, with storms occurring in at least 1866 and 1867 and a strong shower in 1868.

The 1866 return was extensively described by observers in England (cf. Herschel, 1867). Fig 5.1a and Fig 5.1b shows the complete activity curve for the 1866 return. The peak in activity occurred at 233.337°, when the ZHR reached a maximum of 8 000 ± 2 000, as computed from numerous 10 minute counts centred about this time interval from the UK. Note that the radiant from the UK was roughly 20° in elevation - hence the large correction factors. However, this possible overcorrection is balanced somewhat by the loss of shower meteors due to saturation effects as the visible rates were near a meteor per second from the UK. Sufficient observations exist near the maximum to perform a running average of the best observations; this is shown in Fig 5.1c. The curve fit is gaussian of the form

$$ZHR = A\left(\frac{1}{\sigma\sqrt{2\pi}}e^{-\frac{[\lambda_O - \lambda_{O\max}]^2}{2\sigma^2}}\right) \tag{5.1}$$

where A is a normalization constant, σ is the half-width of the distribution, λ_O is the solar longitude (independent variable) and $\lambda_{O\ max}$ is the location of the maximum. The curve is computed by performing a non-linear regression fit to the original smoothed data (shown as black dots). The result for 1866 is σ = 0.017°±0.002° and $\lambda_{O\ max}$ = 233.337°±0.007° (J2000). This implies that to the Gaussian half-width points, the 1866 storm was 25 minutes in duration and peaked at 01:12 ± 0:10 UT on 14 Nov 1866. These results are comparable to those given by Kazimirchak-Polonaskaya et al., 1968 (maximum of 5 - 7 000 at 01:22 UT 14 Nov 1866) and somewhat lower than those found by Jenniskens (1995) (maximum of 17 000 ± 5 000 at 01:00 UT 14 Nov 1866). Yeomans (1981) lists a peak ZHR of ~2000 based on data from Kazimirchak-Polonaskaya et al., 1968 and Olivier (1925), but neither of these two specifically lists hourly rates of 2000 and Olivier lists only an hourly rate of 2800 for two people.

The 1867 shower was hampered by the nearly full moon. Nevertheless, large numbers of observations were made of the storm from Eastern North America. The ZHR profile for the 1867 Leonid storm is shown in Fig 5.2a. The raw observations show a considerable spread nearest the time of maximum, likely a product of the lunar interference. In Fig 5.2b the Gaussian fit to the activity is shown, which yields a maximum time of 233.423°±0.002° with a ZHR of 1200±300 and a half-width of the storm of 0.022°±0.002° or 32 minutes. Note that the ZHR here is a strong lower limit given the lunar interference. From modern observations, a correction of ~4 in the ZHR is typical under these full moon skies, so the true ZHR is most probably in the 4 000 - 5 000 range.

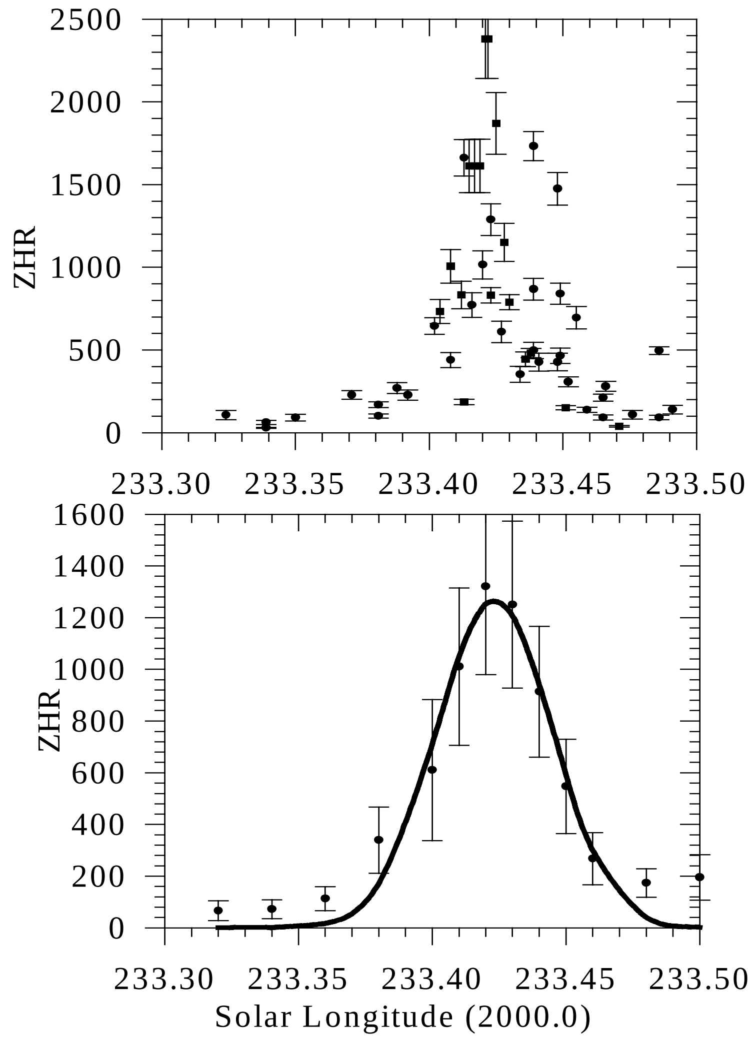


Fig 5.2: ZHR profile for the 1867 Leonid return. Data are from Annals of the Dudley Observatory (1871), Twining (1868), Anon (1871), Leonard (1936) and Stuart (1868). Fig 5.2a (top) shows the activity for the 5 hour period centred about the storm maximum. Fig 5.2b (bottom) shows the Gaussian fit (solid line) to the smoothed data which are binned in a window of 0.05° shifted by 0.02° before 233.38° and after 233.46° and by 0.02° shifted by 0.01° inside this interval.

Jenniskens (1995) finds a very similar time of maximum at 233.713° (B1950) and a compatible (fully corrected) peak ZHR of 6 000 ± 2 000. Kazimirchak-Polonaskaya et al., (1968) list the peak hourly rate as 2184, based on values given in Olivier (1925), This in turn is derived from a report given in Twining (1868) of observations made in Chicago during the peak of the storm in 1867, where 1529 meteors were seen in 42 minutes. Olivier gives this number without further explanation and this value has subsequently been reported in other secondary sources (e.g. Roggemans, 1989). However, the value refers to the number of meteors seen by 8 - 30 observers (Twining, 1868), and is thus many times the single observer rate. Yeomans (1981) lists peak ZHRs as 5 000 based on data given in Kresak (1980), where a peak time 10 hours earlier than listed here is given, but that source reports no reference as to how either the time or strength is found.

The 1868 return occurred under new moon conditions and was widely reported from Europe and North America. Fig. 5.3 shows the activity profile covering the night of Nov 13 - 14, 1868. This display is unusual in that no clear peak is evident and activity remains significant for many hours. The solid line in Fig 5.3 shows the smoothed activity profile confirming little or no variation in the ZHR over a six hour period. Though considerable spread exists in the observations, it is clear that a very strong shower occurred and lasted for many hours. If any short-lived storm occurred, however, it appears to have been missed; the location of the 1866 and 1867 storms would have been over the Pacific in 1868. The peak ZHR in 1868 is approximately 400 ± 200 near 234.2° ± 0.1°. Jenniskens (1995) finds a ZHR of 700 near 233.122° (B1950) but this is based on only two sets of observations, one from Maclear (1869) and one from Grant (1869). Maclear's observations were made under a dense haze from South Africa with a low radiant and are not used here. The hourly rates reported by Kazimirchak-Polonaskaya et al. (1968) of <1200, Lovell (1954) of 1 000 and Yeomans (1981) of ~1 000 are based on Olivier's (1925) report of Kirkwood observing 900 in 45 minutes in the early morning hours of Nov 14 from Indiana. In fact, Kirkwood's original report (Kirkwood, 1869) states that the 900 meteors were seen by "...a committee of the senior class", clearly demonstrating that the 900 in 45 minutes was a group observation and that the single observer ZHR number was much lower, consistent with our ZHR values.

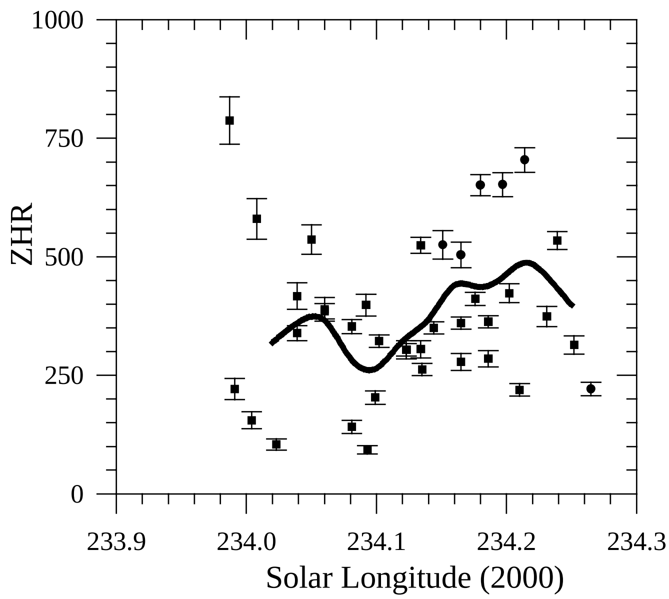


Fig 5.3: ZHR profile for the 1868 Leonid shower. Data are derived from reports in Newton (1869) and Grant (1869). The solid line is a smoothed average of the available observations smoothed over a window of 0.05° shifted by 0.02° from 234°-234.25°.

5.3.3 The 1899 Epoch

Of the showers from 1898-1903, only 1901 and 1903 details signficant activity, with 1898 being a strong shower.

The activity profile for the 1901 shower is shown in Fig. 5.4 and shows the activity profile derived from European and North American observations of the shower in that year. A very clear, consistent rise in activity was reported by observers across Western North

America, culminating near dawn on the West coast when ZHRs approached 250. Accounting for sky conditions and saturation effects, which certainly would have been significant at this level of activity, the peak ZHR in 1901 might well have approached 500 on the basis of these data.

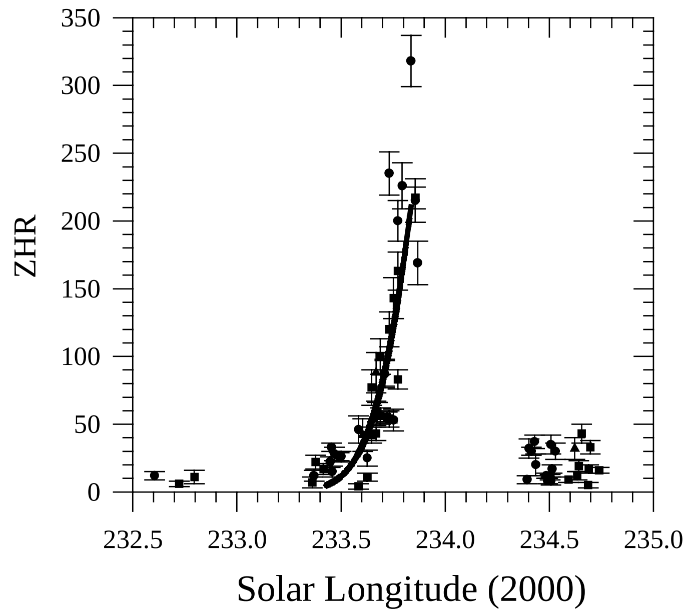


Fig 5.4: ZHR profile for the 1901 Leonid shower. Data are from Payne (1901), King (1902), Upton (1902), Salloms (1902), Dole (1902), Brenke (1902), Leavenworth (1902), Brackett (1902), Denning (1902), and Besley (1902). The solid line represents the ascending portion of the Gaussian fit to the data.

The solid line in Fig. 5.4 shows a Gaussian fit to the activity profile. Note that only the rise and (possibly) the peak were observed; the falling portion of the shower occurred unobserved over the Pacific. The location of the peak from available observations is 233.828° ± 0.014° and the half-width of the Gaussian profile is 0.095° ± 0.01°. This implies that the full-width of the strong outburst in 1901 lasted 5-6 hours (only 3 hours of which were actually observed) but never achieved storm levels. Notations in the literature often cite the 1901 Leonid return as a “storm”, though no observational evidence for this exists. Kazimirchak-Polonaskaya et al. (1968) list rates of 144,000 per hour in 1901 as seen in the UK, clearly a typographical error which has been further reproduced in Yeomans (1981) and Roggemans (1989). Kazimirchak-Polonaskaya et al. (1968) further note hourly rates of 800 from California in 1901, but this value is derived from observations in Claremont, California which are given second hand in Pickering (1902) and elsewhere, whereas the original report (Brackett, 1902) lists 717 seen by 4 observers in the final hour of observation before twilight. The single observer hourly rate is less than 1/3 of this number, consistent with our ZHR values of 250. Jenniskens (1995) lists the 1901 shower as a "storm" with a peak ZHR of 7 000. There is no direct observational evidence for this and we further note that of the four observational sets used in his data, one has an improper time base, having been copied from Denning (1902) where the location for Echo Mountain observatory is mistakenly given as Virginia, when it is in fact in California. The value of 7 000 is calculated assuming a power law fit to the data extrapolated to the ZHR value of 7 000, whereas his individual measured values are no more than 500 as reported. His data are also not as complete as presented here and we suggest that the drop in rates occurring shortly after 233.84° is real. This suggestion is further supported by the reports in Taber (1902) which indicate that no unusual activity was seen in Hawaii, Guam or on steamships in the Pacific on the night of maximum.

The next year of strong activity was 1903 when the Leonid shower returned in full force. The outburst witnessed that year peaked at or slightly after morning twilight in the UK on the morning of Nov 16, where it was widely observed. Observations from North America several hours later show that the outburst had subsided by then and rates were at pre-outburst levels. Nautical twilight in the UK began near 234.05° on 16 November 1903 and this is precisely when rates appear to drop precipitously; clearly the shower ZHR was much higher than the 90 - 100 level calculated from the raw counts in this time period. However, the observations after 234.15° are from North America and represent only one observer (Olivier, 1903). The half-maximum time for the ascending portion of the activity profile is approximately two hours, while the descending portion is indeterminate due to the heavy interference from twilight in the UK (Fig. 5.5). The maximum ZHR is 200 - 250 and, given expected saturation effects and twilight conditions, might well have been as high as 300 - 400. Jenniskens (1995) lists the maximum ZHR in 1903 as 1 400 based solely on the observations from Denning (1904). His data are again extrapolated on the basis of an assumed power-law fit and no actual observational evidence for such high rates exists; to the contrary it appears very unlikely that ZHRs ever exceeded the level of 400 in 1903 and more probable that they were close to 200 - 300 at maximum.

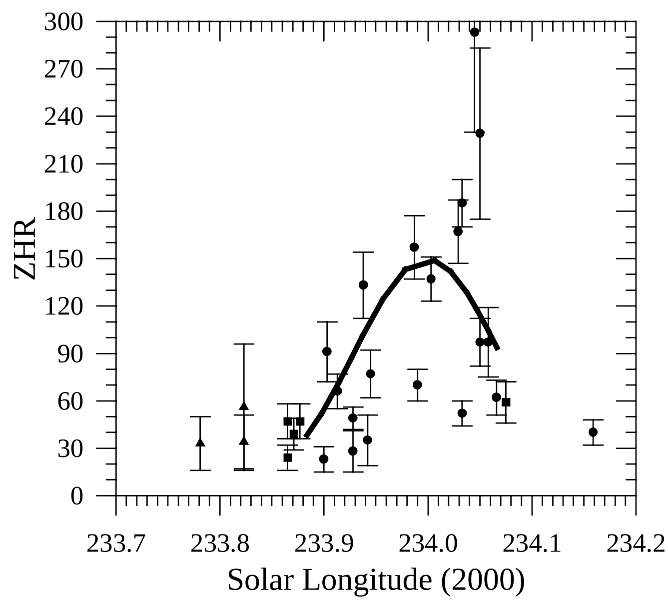


Fig 5.5: ZHR profile for the 1903 Leonid shower. Data are taken from reports contained in Henry (1903), King (1903), Rolston (1903), Young (1904), Rodriques (1904), Denning (1903), (1904), and Besley (1904). The solid line represents the best fit Gaussian to the raw data.

5.3.4 The 1933 Epoch

Clearly heightened activity from the Leonid shower next occurred in 1930. On Nov 17 of that year, observers across North America and the Caribbean reported Leonid rates close to 100/hr with only slight interference from a 26-day old moon. The 1931 Leonid return also produced another modest shower similar to that of 1930, with peak ZHRs at 110 ± 50 based on the average of all counts over the outburst interval, where the counts show nearly constant levels of activity.

The next year, 1932, was widely anticipated as the most probable for the Leonids to produce a meteor storm during the 1933 cycle (Olivier, 1929). Unfortunately, the presence of the moon only four days past full and less than 40° from the radiant, significantly denuded the display. Strong activity, however, was noted from Europe and North America on 16 November 1932. The peak in activity occurred between 234.4° - 234.7° with an apparent ZHR of ~70 and fell to less than half this value on the days before and after the maximum. The true ZHR is probably 3-4 times this value and, given the typical corrections for lunar interference, is suggestive of an actual peak ZHR in the range of 200 - 300. Lovell (1954), Kazimirchak-Polonaskaya et al. (1968) and Yeomans (1981) list the 1932 return as having produced observed rates of 240/hr, implying true ZHRs in the 500 - 1000 range when the effects of lunar interference are factored in and is the apparent reason 1932 is often listed as a "storm" or "near-storm" of the Leonids. This value is based on secondhand reports in Wylie (1933) of counts made in Dubuque, Iowa. The original report (Theobald, 1933) also notes that the peak rate observed was 240/hr. Further reading, however, shows this to be for six observers; the single observer raw rate was 50 - 70, comparable with the apparent ZHRs we have found. We note that within the 2.5 hour window centred about the nodal crossing of Tempel-Tuttle in 1932 (235.06°) only a single hour of observation (from New Zealand) is available at a relatively low radiant elevation. This does leave open the very real possibility that much higher activity took place in 1932 but was missed over the Pacific.

Both 1933 and 1934 produced only modest Leonid displays (see Table 5.1).

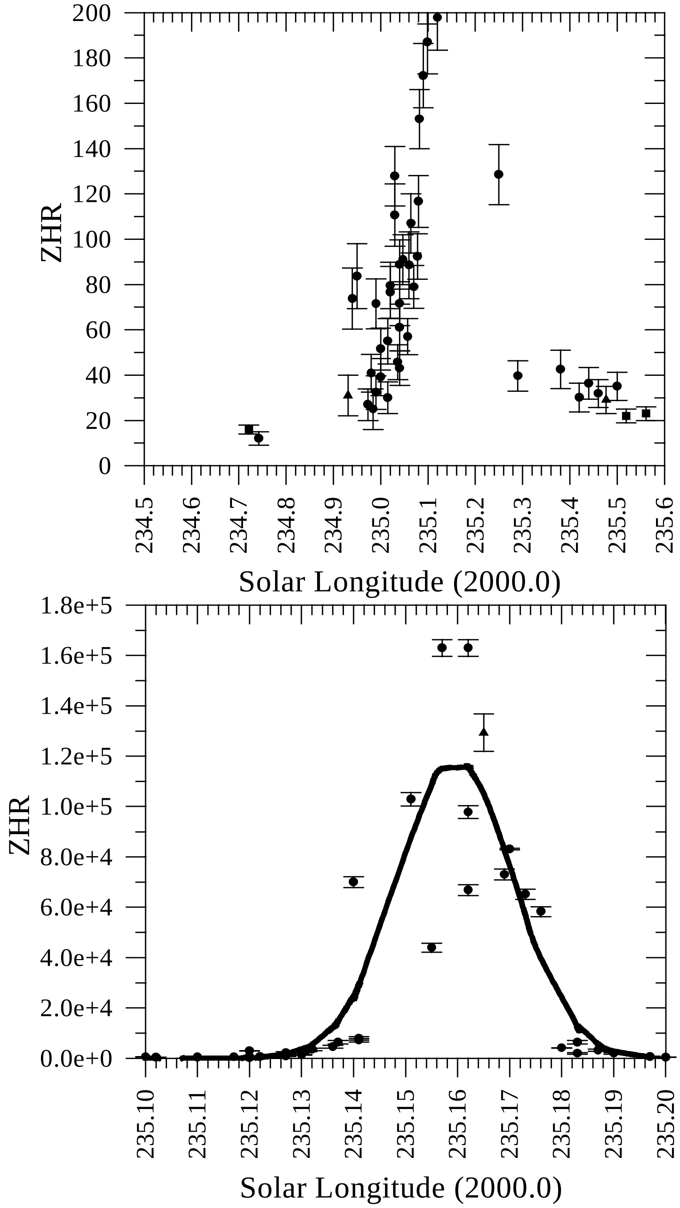
5.3.5 The 1965 Epoch

By the 1965 epoch a general consensus existed that Leonids were no longer able to produce storms. Indeed, McKinley (1961) states that "it is highly improbable that we shall ever again witness the full fury of the Leonid storm". However, in 1966 the largest meteor storm ever recorded was witnessed over Western North America

Lunar conditions in 1966 were ideal, with a new moon occurring on November 12. Observations from 12 - 3 hours prior to the peak of the great 1966 Leonid storm indicate ZHRs of 10-20 (see Fig. 5.6a). Similarly, the ZHR had returned to a level near 20 by 235.5°. The rise toward the storm peak began at approximately 235.02° and ascended rapidly, surpassing the 100 level roughly one hour later at 235.07°. By the end of the next hour, at 235.11°, the ZHR was in excess of 500 and over the next 75 minutes climbed to a peak rate in the vicinity of 75 - 150 000 Leonids/hour (see Fig. 5.6b). The drop from this peak back to a level near 500 took another hour, at which time the final falling portion of the storm went unobserved over the Pacific ocean. It is interesting to note that the full extent of the storm was actually visible only to a few observers in the Central and Western USA and the Soviet arctic who saw the return under near ideal conditions. Observers further East in twilight saw a strong return, but it was only a fraction as intense as for those watching under dark skies: this highlights the high probability that many Leonid storms of the past were undocumented by virtue of poor weather, twilight, the moon and sparse concentrations of observers.

Fitting Eq 5.1 to the full observation set from 235.1° - 235.2° produces a Gaussian fit (shown in Fig. 5.6b) with a maximum at 235.160° ± 0.002°, a peak ZHR of ~115 000 and a FWHM of $\sigma = 0.011° \pm 0.001°$, corresponding to a total duration of 30 minutes. For comparison, Brown et al. (1997) found from Canadian radar observations of the storm (to a limiting meteor magnitude of +6.8) a total duration using a Gaussian fit of 46 minutes. The longer duration of the shower from the radar data is consistent with the expectation that the storm is wider for smaller Leonid meteoroids which are expected to have a larger nodal spread purely on the basis of higher ejection velocities (cf. Jones, 1995).

The highest rates were reported by Milon (1967) from a group of observers under ideal skies at Kitt Peak in the USA. Other observers in less ideal conditions reported rates 2 - 4 times lower (Ashbrook, 1967). However, given the large numbers of Leonids visible, the very subjective methods of determining the rates at the peak, the wide variation in reported ZHRs (from 45 000 - 160 000) at the peak and the uncertain range of observing conditions from the few observers who reported usable information, it is worth stressing that the

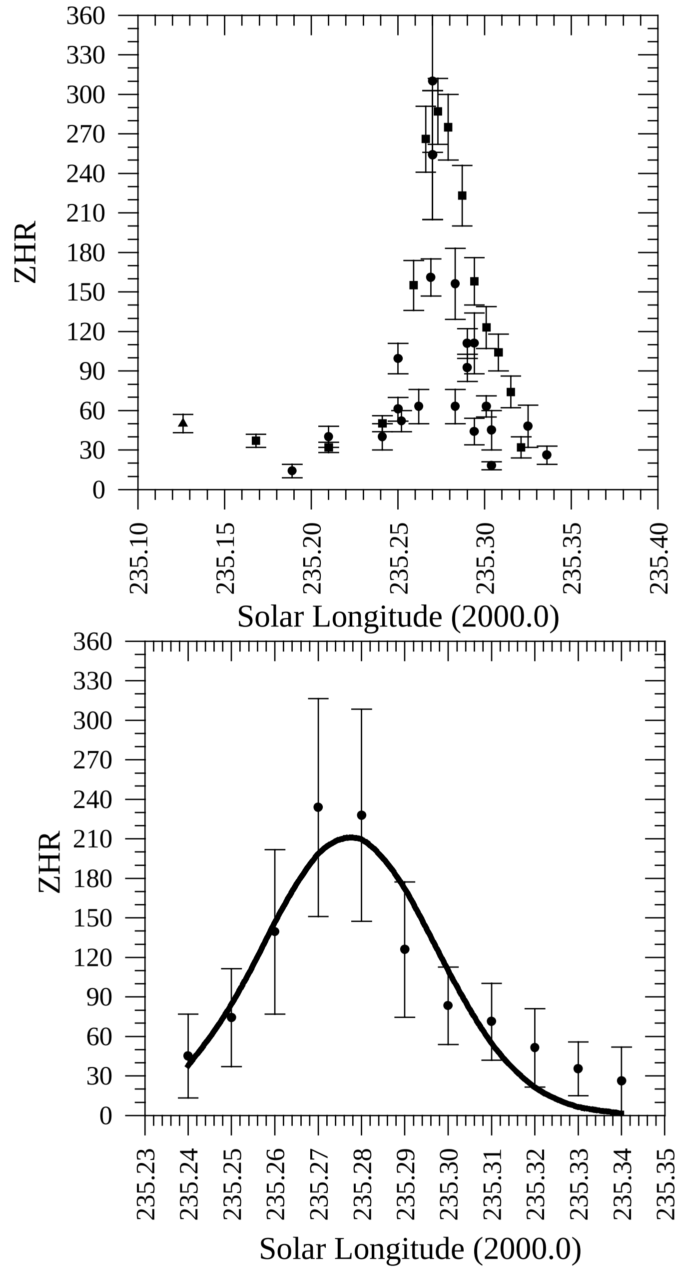


actual peak

Fig 5.6: ZHR profiles for the 1966 Leonids. Data are from Milon (1966), Milon (1967), Bailey (1966), Ashbrook (1967), Rao et al. (1974), Gingerich (1966), Khotinok (1967), Divinskii (1968) and Terentjeva (1967) for the 24 hours around the storm peak (a - top) ZHR profile for the 1966 Leonids near the time of the peak of the storm (b -bottom) with a Gaussian fit to the raw data.

magnitude of the 1966 as inferred purely from visual data is uncertain to at least a factor of 2; a best guess from all available visual observations would place the peak ZHR of the storm between 75 000 - 100 000. It is instructive to note that the lower limit deduced for the peak flux from radar observations in 1966 by Brown et al. (1997) is equivalent to a minimum peak ZHR of 80 000. There are no visual observations from the peak to support the conclusion of Jenniskens (1995) that actual peak ZHRs never exceeded 15 000 during the storm. The widely quoted peak value of 144 000 (cf. Yeomans, 1981; Kazimirchak-Polonaskaya, 1968) is based largely on the account from Milon (1967) which, within error, is not unrealistic, although it is certainly the highest count made by any group of observers.

The 1969 Leonid shower also occurred under good lunar conditions. North American observers reported a distinct, sharp peak in activity near 235.27°, with individual ZHRs as high as 300 (Fig. 5.7a). The Gaussian shape of the outburst is apparent when the data are smoothed as in Fig. 5.7b. The Gaussian shape permits a fit using Eqn 5.1 with a peak at 235.277° ± 0.003°, a maximum ZHR of 210 and a Gaussian width of 0.020° ± 0.003°, corresponding to approximately 1 hour FWHM, about twice as long as the 1966 storm. That the peak occurred so far from the location of the 1966 storm (at which time no enhanced activity was recorded) and the node of the comet suggests a different ejection



origin for 1969.

Fig 5.7: (a - top) ZHR profile for the 1969 Leonids. Data are from Robinson (1970) and Millman (1970). In (b - bottom) a gaussian fit to the original data smoothed in 0.02° bins shifted by 0.01° is shown.

5.4 Recent Activity from the Leonids

From 1969 to the present, numerous visual observations of the shower have been made. Unfortunately, most of these have been made with markedly different techniques and reduced in incompatible ways by various scattered amateur groups worldwide. Between 1988 and 1993 a compatible set of visual observations of the shower was obtained on a global scale using the standardized techniques and reduced in a homogeneous manner. As no single year produced more than a few hundred observed Leonids, and no indications of heightened activity were present in any one year, an average profile of the quiet (or clino-Leonids) part of the stream was generated based on six years of visual observations. The data from all years between 1988-1993 were amalgamated to produce the ZHR curve given in Fig. 5.8.

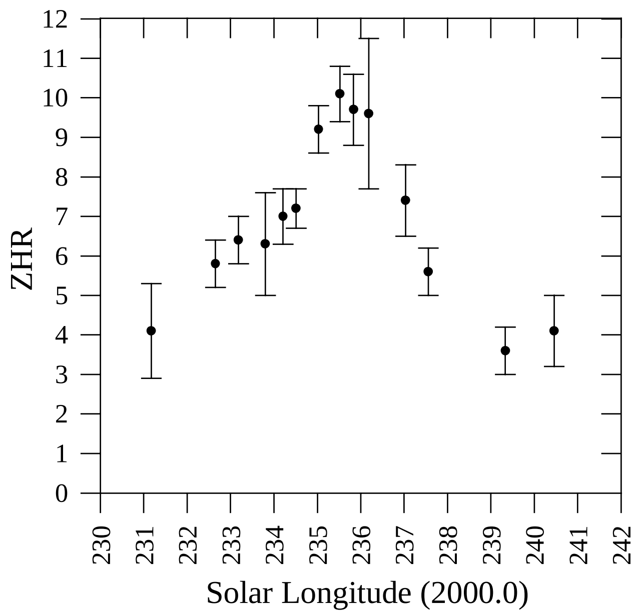


Fig 5.8: Mean ZHR profile for the annual-Leonids averaged from 1988-1994. Data are derived from Brown (1994).

A total of 182 observers contributed 2697 usable Leonid meteors in 1102 observing hours in this period to produce the ZHR-curve. Note that for this curve and for subsequent yearly curves given in Sect 5.4, a fully corrected ZHR is given, i.e. one that corrects for the limiting stellar magnitude reported by observers (see Eq 3.1) and uses either a mean population index (*r*) or *r*-profile for computation of ZHRs. This differs from all previously presented ZHRs and implies that the ZHRs given in this section are more accurate.

As the statistical weight of the sample is still relatively low, we comment only on the apparent time of the maximum which is at 235.5° ± 0.3° (2000.0) with an apparent peak ZHR of ~10. Note that this value is sensitive to the value of *r* used, which in the present case is 2.0 (cf. Brown 1994). We also note that the background sporadic activity is at a level of about 10 - 15/hr in this figure; hence the annual Leonids reach the level of the sporadic background only for a few hours near the time of maximum.

The first enhanced activity of the current Leonid cycle took place in 1994 (Jenniskens, 1996). The full moon resulted in severe noisiness in the individually corrected ZHRs (cf. Brown, 1995 for the original results) with the peak in 1994 occurring near 235.8°. The overall profile is quite wide, having a full duration to half maximum in ZHR of more than one day. The peak ZHR is uncertain near 100.

In 1996 ideal lunar conditions and heightened observer awareness combined for another record number of visual Leonid observations. Fig. 5.9 shows the smoothed ZHR profile centred about the day of maximum (November 17, 1996). The activity features of note are the clear outburst maximum at 235.17°±0.05° and a smaller local maximum at 235.4°±0.1°. The former had a peak ZHR near 90±25 and the latter a value of 45±5. The early outburst maximum was witnessed primarily by a few European observers, but the coverage was sufficient to establish this as a genuine feature (Brown and Arlt, 1997). The outburst is also associated with an increase in the number of faint Leonids. In addition, the outburst was witnessed in radar observations of the shower (Brown et al., 1998) and to a lesser extent by TV observations. The peak flux from the visual observations corresponds to 0.012±0.004 meteoroids km^{-2} $hour^{-1}$ for Leonids of absolute magnitude +6.5 and brighter. The display showed heightened activity relative to the quiet-time profile for several days on either side of the maximum.

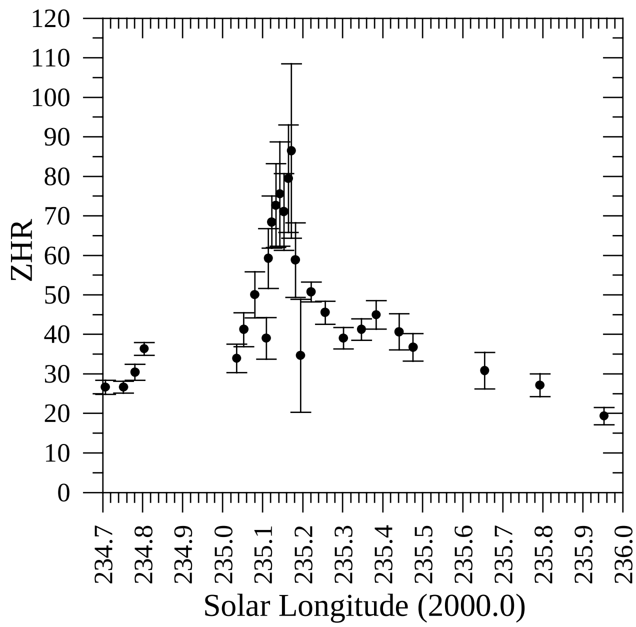


Fig 5.9: ZHR profile for the 1996 Leonids. Derived from Brown and Arlt (1997). Data were smoothed in windows of 0.1° shifted by 0.05° before 235.1° and from 235.2°-235.5° while bins of 0.02° shifted by 0.01° were used from 235.1°-235.2°. The region beyond 235.5° was smoothed in 0.5° intervals shifted by 0.25°

5.5 Discussion

While the results given in Table 5.1 have been computed without resorting to corrections for lunar biases, further examination of the dataset in order to elicit some useful information about the stream requires that some correction be adopted for this strong bias. That the moon significantly affects the observed strength of the stream is obvious from Fig. 5.10, where the Log (Peak ZHR) given in Table 5.1 is plotted versus the age of the moon at the time of the peak of the shower. It is clear that from about 9 - 24 days the trend is toward lower ZHRs, with the strongest displays for which numerical data exist all having been witnessed within a week of the new moon.

Table 5.1: Details of Leonid showers from 1832-present. The Comet Node-$\lambda_{O\,max}$ refers to the difference in time between the observed max and the node crossing. Age of the moon refers to the number of days since new moon at the time of maximum. Min Obs to Node is the closest recorded observation to the nodal passage. The 1998 Observations are preliminary from Arlt (1999). Values with ? are particularly uncertain.

Year	Time of Max (UT) (Nov)	$\lambda_{O\,max}$ J2000.0)	Comet Node - $\lambda_{O\,max}$ (degs.)	Peak ZHR	Activity Width(σ) (degrees) $\times 10^{-2}$	Dur. hours	Age of Moon (days)	Min Obs to Node hours
1832	13.2	233.2	-0.03	2000	-	days?	20	0
1833	13.4	233.15	0.02	60 000	-	~5	1	0
1834	13.25?	232.7	0.47	~60?	-	~7	12	-5
1835	14.8?	234.0	-0.83	~100?	-	-	23	+20
1836	13.3?	233.3	-0.13	100 - 150	-	-	5	+2
1865	13.25?	232.8	0.49	~150	-	-	25	-6
1866	14.05	233.34	-0.05	$8\pm 2\times10^3$	1.7 ± 0.2	4	5	0
1867	14.40	233.423	-0.13	$>12\pm3\times10^2$	2.2 ± 0.2	>5	17	+1.5
1868	14.40	234.2	-0.91	$4\pm2\times10^2$	-	>7	0	+18
1898	15.2	234.3	0.33	50-100	-	~day?	0	-1
1899	15.2	234.0	0.63	20-50	-	~12?	12	+5
1901	15.5	233.828	0.80	250	9.5 ± 0.1	>7	3	0
1903	16.25	234.05	0.58	>200	7.0 ± 0.2	~7	26	-10
1930	17.4	235.3	-0.22	100-140	-	>4?	26	+5
1931	17.35	235.0	0.08	~150	-	~8	7	0
1932	16.25	234.6	0.48	>70	-	>12	18	0
1933	16.4?	234.5	0.58	~50	-	~day	0	-1
1934	17.33	235.2	-0.12	50-60	-	~day	10	+2
1961	-	-	-	~70	-	-	10	-
1963	17.4	234.8	0.33	30	-	>5?	1	+2
1964	17.4	235.6	-0.47	~50	-	24	12	-3
1965	16.6	234.55	0.58	>120	-	~48	23	+1
1966	17.5	235.16	-0.03	$8\text{-}10\times10^4$	1.1 ± 0.1	12	5	0
1967	17.5	234.9	0.23	40	-	-	15	0
1968	17.5	235.65	-0.52	~110	-	3	26	+7
1969	17.4	235.28	-0.15	300	2.0 ± 0.3	3	8	0
1994	18.3	235.8	-0.54	~100	-	14	15	0
1995	18.3	235.5	-0.24	35	-	7	25	0
1996	17.2	235.17	0.09	90	-	2	8	0
1997	17.51	235.22	0.06	100	-	3	19	0
1998	17.05	234.5	0.78	250	-	20	28	0

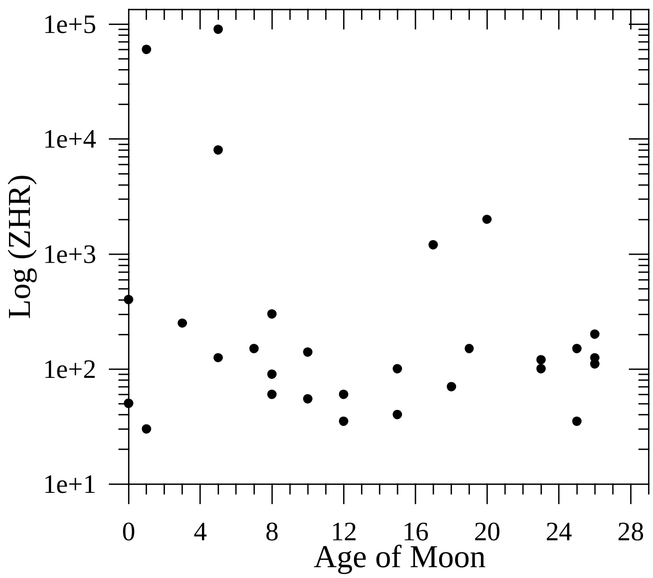


Fig. 5.10: Effect of the moon on activity of the Leonids (from Table 5.1).

From modern visual meteor observations, the difference between the apparent ZHR without sky brightness correction (as utilized here for historical accounts pre-1969) and actual ZHRs, taking into account lunar interference, amounts to approximately a factor of 2 for lunar ages of 9-10 and 24 days after the new moon; a factor of 3 for lunar ages of 11-12 and 22-23 days after new moon; and a factor of 4 for lunar ages at the time of a Leonid maximum from 13-21 days after new moon. In what follows, we have adopted these sets of corrections for pre-1969 observations to generate the most probable maximum ZHR (ZHR_{mp}), independent of the moon.

Of the returns listed in Table 5.1, six had sufficient observations to fit a smoothed profile with Eq 5.1. This allowed estimation of the gaussian width of the profile. This value is plotted against ZHR_{mp} in Fig. 5.11. The trend is toward wider profiles for lower ZHR_{mp}, a reflection of the expected older age of more widely dispersed material (McIntosh, 1973). We note that the fit for five of these six returns is very good; the lack of consistency for the sixth point arises from the 1969 shower which was well observed visually and had a similar profile from radar records (Porubcan and Stohl, 1992); hence we must conclude that the relationship is only approximate for Leonid returns.

Using the five remaining points, however, a good least-squares fit is obtained such that the Gaussian width of the storm component of the stream and the peak ZHR are related via

$$Log(\sigma) = -0.29 - 0.35 Log\left(ZHR_{pm}\right) \tag{5.2}$$

where σ is given in units of degrees of solar longitude. As this dispersion relating to peak activity is likely associated only with the storm component of the stream, the relationship undoubtedly breaks down once ZHR_{pm} is below ~100 when the broader component of activity is dominant.

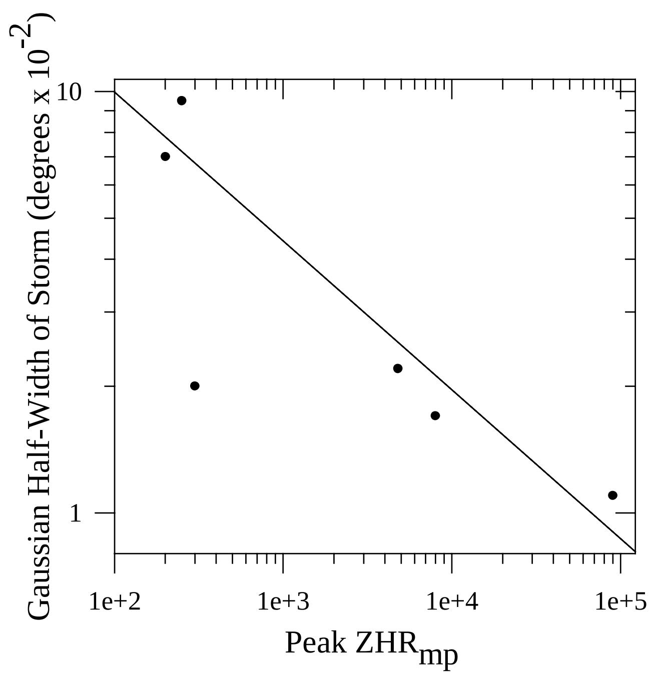


Fig 5.11: Gaussian width of Leonid storms versus most probable ZHR (ZHR_{mp}). Plotted data are from the Leonid returns of 1866, 1867, 1901, 1903, 1966 and 1969.

To determine if this is a reasonable result for the Leonids, we compare these results with those of the IRAS cometary dust trails (Sykes and Walker, 1992). Kresak (1993) has shown that such dust trails are precisely the same phenomenon that produces meteor storms at Earth and thus the width of the two should be similar. If we assume an average mass distribution of *s*=2 within the central portion of the Leonid storms, (cf. Brown et al., 1997 for a discussion of this point in connection with the 1966 Leonid storm), and use the relation between ZHR and flux given in Chapter 3, we can translate Eq 5.2 into a relation between width along the Earth's orbit (σ in km) and spatial density (meteoroids per km^3) of Leonids (larger than mass m in kg) as:

$$S = \frac{6.604\ \sigma^{-2.85}}{m} \tag{5.3}$$

where *S* is the number of meteoroids per km^3 and σ is in km. We assume that the width of the dust trail for 55P/Tempel-Tuttle should be comparable to the average of the short-period comet trails observed by IRAS (found to be 30 000 km at r=1 A.U. (Kresak, 1993), and that the trail is composed primarily of meteoroids 1 mm and larger (10^{-6} kg Leonids) (Sykes et al., 1990). As noted by Kresak (1993), the strongest of the Leonid displays (ZHRs = 100 000) had spatial densities one order of magnitude below the IRAS detection limit. Assuming *s*=2 holds throughout, a Leonid ZHR of 10^6 (which would just be detectable as a trail in the IRAS survey) corresponds to spatial densities of S=10^{-5} meteoroids (>1 mm) per km^3. This corresponds to a σ of 1.5×10^4 km (using Eq 5.3) which is within a factor of two of the mean value found from the IRAS comet trail survey normalized to r=1 AU. Thus it appears Eq 5.2 and 5.3 are representative of the average relationship between the width and meteoroid spatial density within the dust trail of 55P/Tempel-Tuttle at 1 A.U. and are broadly consistent with the IRAS dust trail findings from similar short-period comets.

Similarly, the difference in the widths of the 1966 storm between radar and visual Leonids is a direct measure of the relative spread in ejection velocities for two different mass regimes within the stream. Using the Jacchia et al. (1967) mass-magnitude-velocity relationship, the limiting magnitude of the radar observations (+6.8) corresponds to Leonids with masses near 10^{-8} kg. The visual observations of the storm were effectively representative of Leonids with magnitudes between +3 and +4; these have masses of 10^{-7} kg. The storm width (in degrees of solar longitude) from radar (Brown et al., 1997) was 0.0156°±0.0008° for a gaussian fit, while a similar procedure applied to the visual observations presented here yields a value of 0.011°±0.001°. From the standard theoretical treatment of meteoroid ejection from comets through gas-drag (cf. Jones, 1995), the final ejection velocity is expected to vary with particle mass as $v \propto m^{-1/6}$. Thus the average relative difference in the normal components of the ejection velocity for a decade difference in mass is expected to be 68%. That the visually determined width of the 1966 storm is 70% ± 10% of the radar determined value supports the standard gas-drag ejection treatments and is further evidence that the strongest Leonid storms are very young and have durations controlled by initial ejection velocities. That the locations of ejection of the responsible storm meteoroids along 55P/Tempel-Tuttle's orbit are unknown (if any single ejection location on the cometary orbit is actually entirely responsible for the 1966 storm) implies that this information alone is insufficient for a unique solution to the normal component of the ejection velocity question to be found.

Yeomans (1981) was the first to assume explicitly that the strongest shower peaks should occur close to the nodal longitude of the comet. As the closest distance between the comet and Earth increases, it would be expected that orbits of the dust encountered would be the most different from those of the parent comet and hence most likely to have a peak at a longitude different than the comet's nodal longitude.

In Fig. 5.12 we investigate this assertion by plotting the peak ZHR against the difference between the time of nodal passage and the time of observed maximum. There is nearly an even split with as many maxima occurring before the nodal passage as after.

It can be seen that as the peak ZHR_{mp} increases, there is a strong tendency for the shower maxima to occur closer to the nodal longitude of the comet. Intriguingly, most of the strongest showers peak 0.5 - 2 hours after the nodal point of Tempel-Tuttle. While this may be a simple statistical fluctuation related to the small number of points involved, it is worth noting that these five storms have among the best determined locations of peak activity. For returns where the Peak ZHR was at a sub-storm level (<500), there is no clear pattern. This suggests that the major storms are of distinct (probably very young) origin relative to all other Leonid returns. The observed negative lag for the major storms (i.e. peak activity reached after the nodal longitude of the comet), may indicate an asymmetry in dust ejection normal to the cometary orbital plane. The larger nodal longitudes for the storms could indicate that dust ejection is in the positive normal direction to the cometary orbital plane and of order ten meters per second if ejected near perihelion.

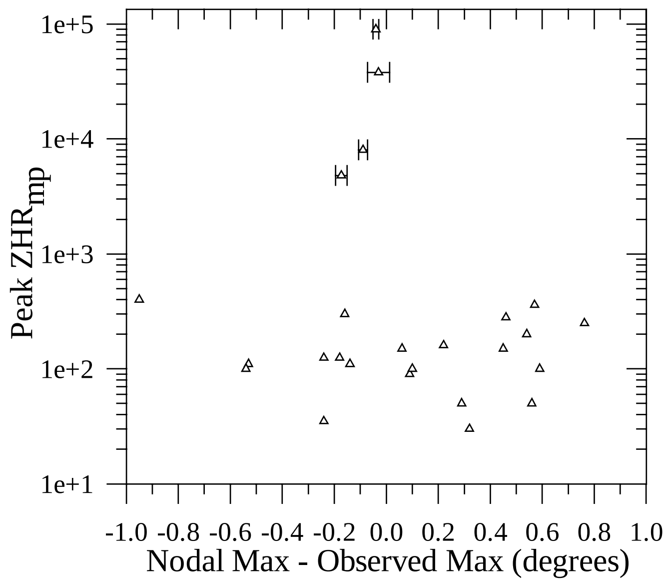


Fig 5.12: The most probable peak ZHR for all years given in Table 5.1 as a function of the difference in time between the observed peak activity and the nodal point of the comet (in degrees).

In an effort to determine the approximate relative distribution of dust about 55P/Tempel-Tuttle, the 30 independent ZHR determinations given in Table 5.1 have been combined with the orbital encounter geometry for each return in Fig. 5.13. Here Log (ZHR) is given in contour form. Note that these data include observations up to 1997. While this contour plot changes somewhat depending on the precise contouring technique applied, the overall shape of the distribution remains constant. As has been noted previously by numerous authors (cf. Yeomans, 1981; Wu and Williams, 1992), our results are consistent with the greatest dust concentration being spatially outside the comet's orbit and temporally behind it. Note that in the data used here (post 1799) the Earth has only sampled dust from outside the comet's orbit, so from this alone we can say nothing about the concentration inside the comet's orbit (cf. Yeomans, 1981 or Mason, 1995 for a complete discussion of the dust distribution with reference to older showers encountered inside the comet's orbit).

Using these results to forecast activity over the next few years, it appears most probable that a Leonid storm of modest strength is most likely in the year 1999. Peak ZHRs of order 1000 during either of these two years are ostensibly predicted by examination of the overall distributions, but the paucity of datapoints in the region nearest these years suggests these values should be viewed with caution.

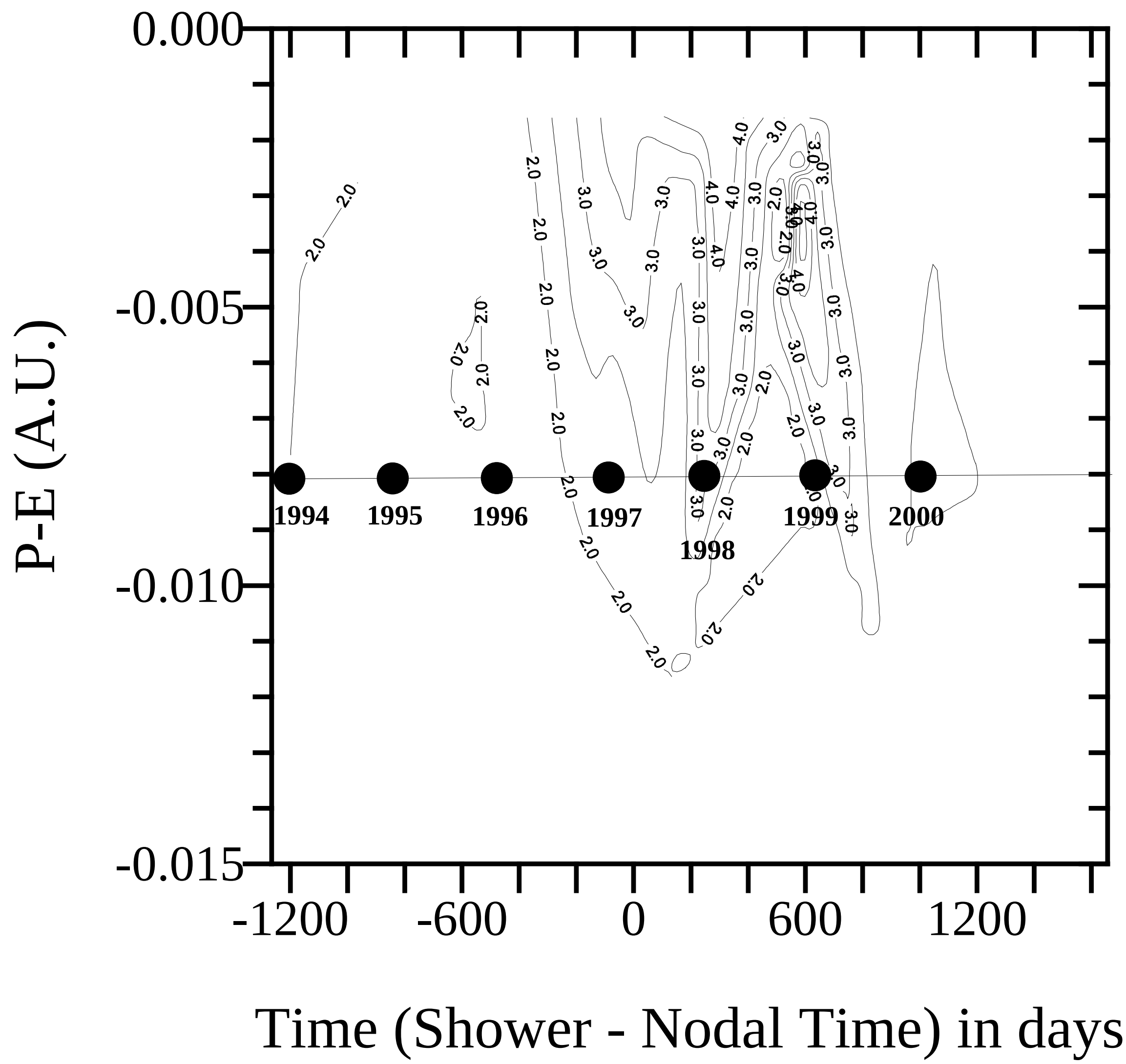


Fig 5.13: Contour distribution of dust density about 55P/Tempel-Tuttle. Contours are in units of Log (ZHR_{mp}). P-E (A.U.) is the closest distance between the cometary orbit (determined at perihelion for a given Leonid epoch) and the Earth's orbit in Astronomical Units. Time on x-axis is a measure of the observed time of the shower (in days) relative to the comet's nodal passage.

5.6 Conclusions

Examination of the original accounts of past Leonid storms has led to a revised list of times and strengths of past Leonid showers for the post-1832 era as summarized in Table 5.1. Based on the observational record alone it is concluded that:

- From the detailed yearly results, it is apparent that the activity of the shower in numerous years as quoted in many secondary sources is in error. The strongest of the Leonid storms show activity near the maximum which is well represented as Gaussian in shape.
- The profiles of the various Leonid returns suggests that there are three distinct components to the Leonid shower, some or all of which may be visible in any one year. A broad annual component which lasts for 3-4 days and barely reaches sporadic levels is almost certainly present every year and is the oldest section of the Leonid shower. In addition to this, a more moderate level of extended activity, often accompanied by brighter Leonids (an extended component), is visible in some (but not all) of the years near the time of Tempel-Tuttle's perihelion passage. This extended component may last up to two days (i.e. 1965) and may produce ZHRs as high as several hundred (i.e. 1868) for many hours. The extended component has been witnessed in every Leonid return from 1994-present. These two distinct components have been previously merged together and termed clino-Leonids.
- The last component is the storm component or ortho-Leonids. This part of the stream is undoubtedly the youngest, is characterized by short, intense activity and is generally present most often in the one or two years immediately following the passage of the comet. It represents the passage of the Earth in or near a dense structure associated with one of the last few returns of Tempel-Tuttle, analogous to IRAS dust trails (cf. Kresak 1993).
- Using the best available data for the duration and strength of five of the ortho-Leonid storms, a relationship between the width of the storm component and the peak spatial density is derived which is broadly consistent with the findings from the IRAS cometary trail survey of comparable short-period comets.

- Differences in the duration of the 1966 storm at two different limiting masses reveal the duration of the storms to be consistent with that expected, based on initial ejection velocities which follow standard gas-drag treatments.
- A possible systematic trend in the location of the peaks of storms after the nodal longitudes of the parent comet may represent an asymmetry in dust production normal to the cometary orbital plane.
- Interpolation of the dust density about 55P/Tempel-Tuttle for the years 1998 - 2000 suggests that a strong 1966-class storm is unlikely, but that ZHRs of order 1000 may be reached in 1999.

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